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Army Construction Engineering Research Laboratory
Champaign, Illinois

December 1972

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(Addenda to Technical Report M-24)

THE INTRODUCTION OF DISCONTINUITIES IN HIGH STRENGTH STEEL WELDMENTS

by
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December 1972

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13. ABSTRACT
The objective of this study was to develop methods for consistently creating porosity, slag inclusions, lack of fusion, and hydrogen cross-cracking discontinuities in welds to evaluate their effects on the properties of welds. To accomplish this objective, weld deposition procedures were altered systematically to develop welding techniques capable of producing a specific discontinuity type and size. The techniques used included both electrical and mechanical perturbations of the welding parameters.

It proved possible to implant weld discontinuities with good reproducibility. It was found, however, that mechanical perturbations were more reliable for accurate reproduction of discontinuities.

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weld discontinuities
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FOREWORD

This investigation was conducted by members of the Civil Engineering Department of the University of Illinois at Urbana-Champaign, Illinois under the sponsorship of the Construction Engineering Research Laboratory (CERL). The work was performed under work unit 009, "Engineering Criteria for Welds," of task 02 of the OMA Program 4DM78012AOK1, "Engineering Criteria for Design and Construction." The OCE technical monitor was Mr. I. A. Schwartz. Work is being continued under the same work unit which has been renumbered ACK1-02-102.

CERL personnel directly concerned with this study were Messrs. K.W. Carlson, R. Neathammer, and Dr. R. Quattrone. The University of Illinois personnel were Dr. F.V. Lawrence, and Dr. J.B. Radziminski. The Director of CERL was Col E.S. Townsley and the Chief of the Materials Division was Mr. E.A. Lotz.

CONTENTS

THE INTRODUCTION OF DISCONTINUITIES IN HIGH STRENGTH STEEL WELDMENTS

1 INTRODUCTION

Objective. The objective of this investigation was to develop techniques for producing controlled discontinuities in weldments. Such information is necessary as a preliminary step in an in-depth, long range investigation of the effects of weld discontinuities on mechanical behavior of the joint.

Background. When products are fabricated by welding, rarely are the weld deposits free of discontinuities. The field construction environment increases the possibility of discontinuity formation because it is generally not ideal. Factors such as temperature, fit up, accessibility, weld position, and restraint can vary considerably. If not properly compensated for, such variations can result in weld discontinuities.

Discontinuities in weldments can be of many types. Cracks, porosity, lack of fusion, incomplete penetration, undercut inclusions, and burnthrough are some of the discontinuities commonly found in construction that can effect the serviceability of the product.

The effect of all discontinuities is not the same. Factors such as size, shape, distribution, orientation, type of service, material properties, temperature, and discontinuity type play an important part in determining the effect of discontinuities. It is not yet possible to quantitatively describe the effects of all these factors on the serviceability of a weldment because no proven relationships exist between these factors and the properties of the weldment. Such quantitive relationships would be extremely useful to the application of nondestructive inspection of fabricated structures because they could predict the performance of a structure more accurately than the current standards. In such an application, there could be a considerable cost saving by assuring that repairs be made only in weldments actually requiring them and by assuring that other welds can meet the intended service requirements.

The overall objective of this work unit is to develop equations which quantitatively relate type, size, shape, location, and orientation of weld discontinuities to the mechanical properties of a weldment. Such equations could then serve as the basis of a new set of specifications for inspection of welded structures.

The steps necessary for successful completion of the work unit are the following:

1. Develop techniques for producing controlled discontinuities of a specific type in weldments. The techniques should employ weld perturbation rather than the introduction of foreign particles since the former is the common source of discontinuities in actual service.

2. Develop nondestructive inspection techniques and procedures to accurately describe the discontinuities in detail.

3. For each type discontinuity, develop tentative equations describing the relations of its variables to the mechanical properties.

4. Fabricate specimens containing only the desired discontinuity using the techniques developed in step 1. Inspect them, using the techniques developed in step 2. Predict their behavior using the tentative equations developed in step 3.

5. Conduct mechanical tests to verify the predictions of step 4.

6. Modify the equations of step 3 to incorporate the results of step 5. 7.

7. Repeat steps 3-6 for other discontinuity types or other loading conditions.

In this program the mechanical properties of interest include the yield strength, ultimate tensile strength, ductility, toughness, and fatigue life of weldments in high strength steel. The discontinuity parameters to be correlated for their effects on the above quantities are type, size, shape, location, orientation, and distribution. The weld discontinuities to be included in the study are cracks, three types of porosity, lack of fusion, and slag inclusions.

Hypothesis. Theoretically a set of equations based upon the principles of fracture mechanics can be devel-

oped to predict the behavior of a weldment. Applying these principles, it should be possible to determine what the important discontinuity variables are and what their interrelations would be. If such a set of equations can be developed and if the nondestructive examination of the weld discontinuities can be made with sufficient sensitivity to accurately describe the discontinuities, the mechanical properties of the weldment may be predicted.

Approach. This interim report documents the completion of the first step, the development of techniques for producing controlled discontinuities in weldments. Additional interim reports will be issued upon the completion of steps 3 through 6, for each of the discontinuity types or loading conditions. Step 2, the development of accurate nondestructive inspection techniques, is a continuing effort under research project "Nondestructive Testing for Field Welds."

2 TEST PROCEDURES

Implantation of Discontinuities. Intentional perturbations of the normal welding conditions were performed in order to implant the discontinuities. These perturbations were performed during the first pass and covered by subsequent sound weld passes.

The perturbations attempted were various combinations of voltages and currents in the gas-metal-arc (GMA) process for porosity and lack of fusion, variations in GMA shielding gas for porosity, irregular welding patterns using shielded-metal-arc (SMA) electrodes for slag inclusions, and various techniques of injecting hydrogen into the molten weld metal for hydrogen cross-cracking.

Table 1
Chemical Composition of HY-130(T) Base Metal*

Heat No.	5P2004
Chemical Constituents	Percentage
C	0.11
Mn	0.88
P	0.003
S	0.006
Si	0.35
Ni	4.95
Cr	0.53
Mo	0.50
V	0.06
Cu	0.07

* Data supplied by US Steel Corporation.

A high-strength steel, HY-130(T), and suitable SMA and GMA welding electrodes were used in this investigation. All welded test specimens were fabricated from one-inch thick plate stock of HY-130(T) steel obtained from U.S. Steel Corporation; the chemical composition and mechanical properties are presented in Tables 1 and 2, respectively. The as-deposited chemical composition of the Linde 140 GMA, bare electrode welding wire, and of the McKay E12018 and E14018 covered electrodes used in the preparation of the presentation specimens are given in Table 3. The shielding gas used in the GMA process was 98% Argon – 2% Oxygen.

The weld passes were deposited in V-grooves machined in plates of HY-130(T) base metal. The grooves simulate one-half of a full-penetration, double-V butt weld. The experimental plates used for develop-

Table 2
Mechanical Properties of HY-130(T) Base Metal*

		Properties in Longitudinal Direction				
Heat Number	Plate Thickness (Inches)	Yield Strength** (ksi)	Ultimate Tensile Strength (ksi)	Elongation to Fracture in 2 inches (percent)	Reduction in Area (percent)	Charpy V-Notch Energy (ft-lbs @ 0°F)
5P2004	1	141.6	152.0	20.0	63.8	90

* Data supplied by US Steel Corporation.
** 0.2 percent offset.

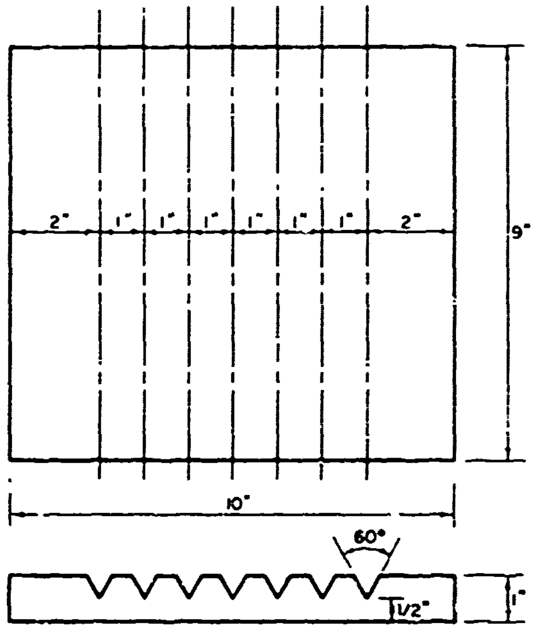

Figure 1. Grooved Plate for Experimental Welds.

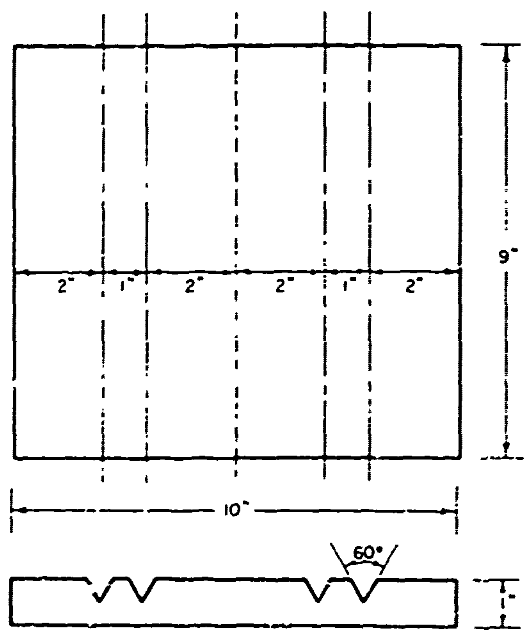

Figure 2. Layout of Grooves for Presentation Specimens. Two specimens were made from one plate and were cut apart along the dashed line.

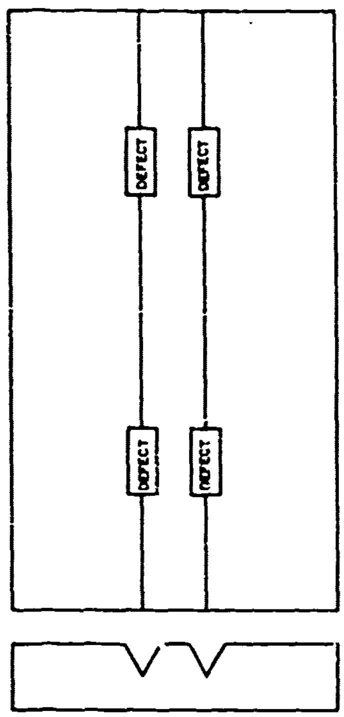

Figure 3. Schematic Representation of Position of Defect Areas in Presentation Specimen Two nominally similar weld passes were created.

Table 3
Chemical Composition of Electrodes for Welding HY-130(T) Plates*

Manufacturer	Linde Division, Union Carbon Corporation		McKay Company
Electrode Designation	Linde 140	McKay 12018	McKay 14018
Electrode Type	1/16" Bare-Electrode Wire	5/32" Covered Electrode	5/32" Covered Electrode
Heat No.	106140	–	1P1375
Chemical Constituents	Percentage	Percentage	Percentage
C	0.11	0.07	0.077
S	0.007	0.022	0.003
P	0.008	0.015	0.003
Mn	1.72	1.50	1.91
Si	0.36	0.40	0.42
Ni	2.49	2.00	2.08
Cr	0.72	0.45	0.71
Mo	0.88	0.40	0.43
V	0.01		
Cu	0.08		

* Data supplied by manufacturers, analysis on deposited weld.

ing the techniques were cut as shown in Figure 1 while the presentation specimens used for final demonstration of results were cut as shown in Figure 2.

As a standard of reproducibility, two consecutive welds with two defective regions in each were produced as shown schematically in Figure 3. This method has been found to give a good measure of reproducibility and a feeling for the discontinuity variations resulting from inherent fluctuations in the welding conditions.

Verification of Discontinuities. To ascertain whether the desired discontinuity, and only the desired discontinuity, was successfully implanted, each weldment was inspected both nondestructively and destructively. Radiography was the nondestructive technique employed. To conclusively verify the nature and size of the discontinuity, the weldment was sectioned at the point where the radiograph indicated the discontinuity to be and examined metallographically.

3 RESULTS AND DISCUSSION

Implantation of Discontinuities. Internal discontinuities were implanted by perturbations of normal electrical conditions, shielding gas conditions, and welding skill conditions. A summary of the successful perturbations used to produce the final presentation specimens appears in Table 4.

Porosity. Three types of porosity were produced in this program, isolated or dispersed pores, linear porosity, and clustered porosity. The nature of the porosity was used to define the three general types. Each of the three types of porosity was produced by the GMA process.

The term "isolated pores" refers to a single void or

Table 4
Summary of Final Presentation Specimens

Specimen Number*	Flaw Type	Perturbation
PS-1	Clustered Porosity	No shielding gas
PS-5	Lack of Fusion	Reduced current
PS-6	Linear Porosity	No oxygen in shielding gas
PS-7	Isolated Porosity	Increased current
PS-8	Slag Inclusion	Positioned "off-center" of the weld
PS-10	Cross-Cracking	No pre-heat, 1.5% H_2 in shielding gas

* Presentation Specimens 2 through 4 were discarded because of equipment problems. Presentation Specimen 9 showed no cross-cracking when the McKay 14018 electrode was used therefore different procedures were tried for PS-10. Note that each specimen contains 2 welds (4 defects). See Figure 2.

to a few dispersed voids which are located in the same region of the weld and which are distinct and easily discernable from one another. This broadened definition of isolated porosity was used because of the extreme difficulty in producing a single, isolated pore. Producing a single pore is difficult because pore formation is a nucleation and growth process; therefore, its kinetics complies with the laws of statistical thermodynamics. When the conditions are such that pore nucleation is favored, it is probable that two or more pores will nucleate unless the conditions for pore nucleation can be changed immediately.

Isolated pores were produced by intensifying the arc power by increasing either the voltage or the current. However, increasing the voltage was not considered satisfactory since the pores produced would be accompanied by lack of side wall fusion. Therefore, increasing the current, which produced solely isolated pores, was considered to be the only satisfactory perturbation for this defect.

Linear porosity is defined as a series of pores arranged in essentially a straight line over some length of the weld. Linear porosity was most successfully produced by shutting off the oxygen in the shielding gas. An unstable arc results which is due, in part, to variations in the amount of iron oxide on the plate surface. Appreciable fluctuations in the cathode voltage drop occur and, consequently, the arc wanders as it seeks a position requiring the lowest drop. The porosity is produced when the unstable arc causes air to be entrapped under the molten pool. Linear porosity was produced in the presentation specimen, PS-6.

Clustered porosity is defined as a concentration of many closely spaced pores which, consequently, are often not easily distinguishable one from another. Clustered porosity was most effectively produced by shutting off the shielding gas completely. The weld metal is contaminated by reaction with oxygen in the atmosphere at the melting point. Since the solubility of oxygen in steel decreases rapidly as temperature decreases clusters of pores form as a result of gas entrapment during cooling. The formation of CO and CO_2 and subsequent release also adds to the number of pores. Clustered porosity was produced in presentation specimen, PS-1.

Lack of Fusion Lack of fusion, like porosity, was produced using the GMA process. The goal of this phase of the investigation was to produce a segment of the weld containing lack of fusion of a specific length. Lack of fusion was most effectively produced by lowering the current (see Table 5). The length of the lack of fusion is proportional to the length of time the current is held at the low value. Lack of fusion was produced in presentation specimen PS-5.

As mentioned previously, lack of fusion also commonly occurs when the voltage is increased to large values. However, as pointed out, this procedure was

Table 5
Welding Parameters for Defect Formation

Defect Type	Filler Metal	Electrode Diameter (inches)	Current (amps)	Voltage (volts)	Travel Speed (in/min)	Preheat Temperature (°F)	Shielding Gas
Sound Weld	Linde 140 (GMA)	1/16	300	28	12.0	250	98% Argon-2% O_2
Isolated Porosity	Linde 140 (GMA)	1/16	375	28	12.0	250	98% Argon-2% O_2
Linear Porosity	Linde 140 (GMA)	1/16	300	28	12.0	250	100% Argon
Clustered Porosity	Linde 140 (GMA)	1/16	300	28	12.0	250	None
Lack of Fusion	Linde 140 (GMA)	1/16	240	28	12.0	250	98% Argon-2% O_2
Slag Inclusion	McKay 12018 (SMA)	5/32	185	24	9.5	250	Not applicable
Hydrogen Cross Cracks	Linde 140 (GMA)	1/16	300	28	12.0	75	97.5% A-1% O_2-1.5% H_2

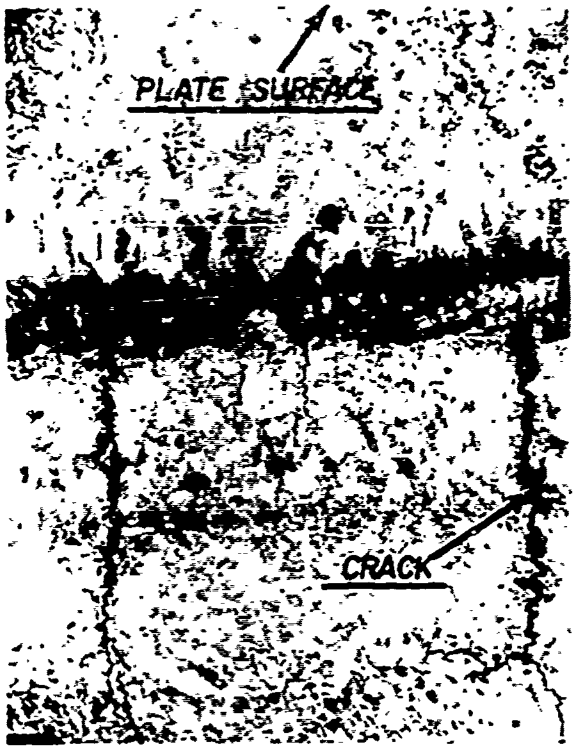

Figure 4. Macrophotograph of Hydrogen Cross-Cracks obtained in weld metal in PS-1C. The section is parallel to the axis of the weld and perpendicular to the surface. Two percent Nital etch, magnification 10X.

Figure 5. Macrophotograph of Clustered Porosity in PS-1. Two percent Nital etch, magnification approximately 4X

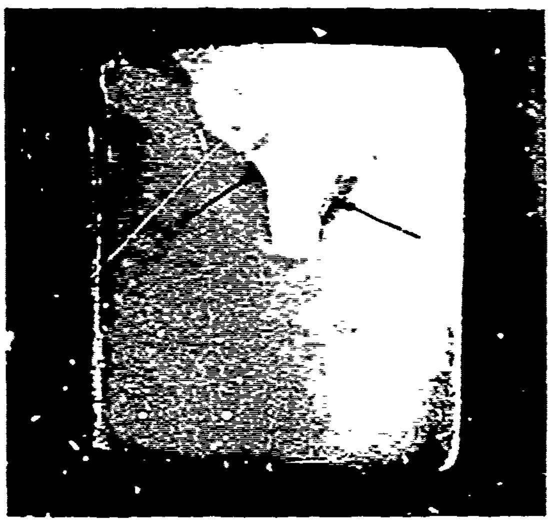

Figure 6 Macrophotograph of Lack of Fusion (arrows) in PS-5. Two percent Nital etch, magnification approximately 4X.

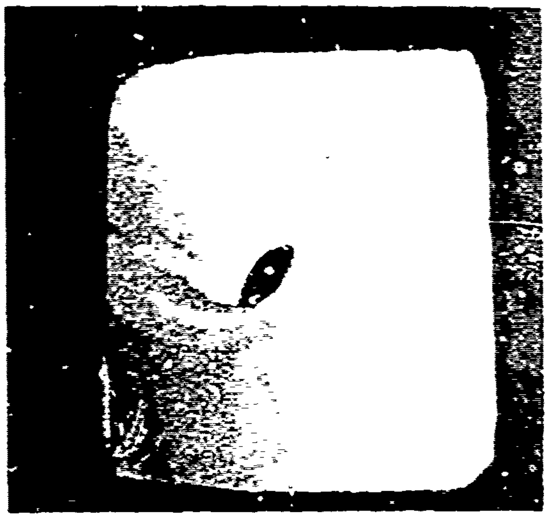

Figure 7. Macrophotograph of Slag Inclusion in PS-8. Two percent Nital etch, magnification approximately 4X.

considered unsatisfactory because the lack of fusion is usually accompanied by large pores; thus, this procedure was not used.

Slag Inclusions. Slag inclusions were implanted using E12018 covered electrodes in the shielded metal-arc (SMA) process. The electrodes used in the SMA process operate with heavy slag action. The heat of the arc melts the covering forming a slag and the drop is completely slag-covered during transfer. Before solidification of the weld, the slag being lighter than the metal floats to the surface of the weld where it solidifies and is cleaned off. If the electrode is positioned off the center-line of the V-groove, this floating action is obstructed and slag is trapped between the weld deposit and the side of the groove.

It should be noted that to control slag entrapment, it was necessary to grind a radius at the root of the V because with a sharp V it was not possible to prevent a thin line of slag from being entrapped in the root along the entire length of the weld. By positioning the arc off-center on the first pass, slag inclusions were produced as in the presentation specimen, PS-8.

Hydrogen Cross-Cracking. The three essential conditions necessary to produce hydrogen cross-cracks are a source of hydrogen, the formation of martensite, and tensile stress.

The hydrogen cross-cracks were produced using the GMA process. The normal parameters for a sound weld were used; however, the shielding gas used was a mixture of 97.5% argon – 1% oxygen – 1.5% hydrogen and the weld was made on a plate which was not preheated (see Table 5). In this way the cooling rate favored martensite formation. The combination of martensite formation and constraint from the base plate produced a sufficient stress. Many cracks appeared transverse to the welding direction. The cross-cracks produced in PS-10 can be seen in Figure 4, which is a section parallel to the welding direction and perpendicular to the plate surface.

Cross-cracking was attempted in PS-9 by using McKay 14018 SMA electrode, which had been reported to be susceptible to hydrogen cross-cracking.[1] However, no cracks were observed when this electrode was used in this investigation. Therefore, the GMA process was used.

Nondestructive and Metallographic Examination. Radiographic examination indicated that only the desired discontinuities were produced in the presentation specimens. Guided by the radiographic indications presentation specimens 1, 5, 8 and 10 were sectioned to verify the existence of the desired discontinuities, their physical dimensions and position in the weldment. These specimens contained clustered porosity, lack of fusion, slag inclusions, and cross-cracking, respectively. No attempt was made to section specimens containing isolated pores because of the difficulty in exactly cutting in the plane of the pore. Figures 4, 5, 6 and 7 show macrophotographs of the polished and etched sections of PS-10, 1, 5, and 8, respectively. The desired discontinuities were present and in the positions indicated by radiography.

4 SUMMARY

Techniques for implanting three types of porosity, lack of fusion, slag inclusions, and hydrogen cross-cracking were successfully developed. Non-destructive and metallographic verification indicate that the desired discontinuities were implanted.

When the perturbations involved the shielding gas, control of the size of the discontinuities was good. On the other hand, electrical perturbations did not yield discontinuities as easily controllable. The amounts of linear porosity, clustered porosity and hydrogen cross-cracks are easily controlled because they were obtained by altering the shielding gas which was automatically controlled by solenoid operated valves. Slag inclusions also are controllable when the welder is sufficiently skilled to keep the slag entrapped during the deposition process. However, high controllability of size and number in the case of isolated porosity is still quite difficult to obtain.

Difficulties arise when electrical perturbations are employed to produce a discontinuity. The voltage and current fluctuate greatly during the welding process due to environmental and common electrical conditions. An alteration in the voltage or current requires a considerable time lapse before the discontinuity-

[1] J.B. Radziminski, F.V. Lawrence, Jr., T.W. Wells, R. Mah, and W.H. Munse, *Low Cycle Fatigue of Butt Weldments of HY-100(T) and HY-130(T) Steel* (University of Illinois, 1970).

producing conditions are attained. Furthermore, once the discontinuity-producing conditions are reached, the altered parameters are still subject to random fluctuations. The inability to properly control the electrical parameters makes the fabrication of controlled-size discontinuities difficult. However, automatically adjusting the welding parameters may minimize this difficulty.

5 CONCLUSIONS

Implantation of Discontinuities. Using the electrical and mechanical perturbations described in this report, three types of porosity, lack of fusion, slag inclusions, and hydrogen cross-cracks were intentionally implanted in weldments. When the perturbations involved the shielding gas, control of the size of the discontinuities was good. On the other hand, electrical perturbations were not as easily controlled because of the random electrical fluctuations inherent in welding and the inability to properly control the electrical parameters manually.

Future Work. The next reported phase of this program will be an evaluation of the effect of varying amounts of cluster porosity of the tensile properties of welds in T-1 steel. Future interim reports will present the results of investigations of the effects of other discontinuity types or loading conditions.

REFERENCE

Radziminski, J.B., F.V. Lawrence, T.W. Wells, R. Mah, and W.H. Munse, *Low Cycle Fatigue of Butt Weldments of HY-100(T) and HY-130(T) Steel* (University of Illinois, 1970).